A Dancing Robot for Rhythmic Social Interaction

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ABSTRACT

This paper describes a robotic system that uses dance as a form of social interaction to explore the properties and importance of rhythmic movement in general social interaction. The system consists of a small creature-like robot whose movement is controlled by a rhythm-based software system. Environmental rhythms can be extracted from auditory or visual sensory stimuli, and the robot synchronizes its movement to a dominant rhythm. The system was demonstrated, and an exploratory study conducted, with children interacting with the robot in a generalized dance task. Through a behavioral analysis of videotaped interactions, we found that the robot's synchronization with the background music had an effect on children's interactive involvement with the robot. Furthermore, we observed a number of expected and unexpected styles and modalities of interactive exploration and play that inform our discussion on the next steps in the design of a socially rhythmic robotic system.

Figure 1: Keepon dancing with a child.

Categories and Subject Descriptors

H.1.2 [**Models and Principles**]: User/machine systems; I.2.9 [**Artificial Intelligence**]: Robotics; J.4 [**Social and Behavioral Sciences**]: Psychology, Sociology; J.5 [**Arts and Humanities**]: Performing arts

General Terms

Design, Experimentation, Human factors

Keywords

Human-robot interaction, Social robotics, Children, Dance

1. INTRODUCTION

Socially interactive robots are being designed and built for the purposes of exploration (performing scientific experiments to learn about human behavior or cognition), service (assisting in labor, communication, or access to information), and influence (education, therapy, entertainment, or aesthetic experience). Regardless of motivation or application, the success of a face-to-face human-robot social interaction depends strongly on the robot perceiving the spatial and temporal properties of the interaction and behaving in a coordinated manner. Robotics researchers have devoted many years of work to interactive skills such as turn-taking, gestures, and emotive expression, all of which are important for effective communication. However, an increasing amount of attention is being directed to the idea that the comfort and "naturalness" of an interaction may depend on a foundation of far more subtle and fine-grained coordination between the sounds and movements of the two interactors.

Dance, as a human art form, can be seen as a representation of the *imitation* and *pattern*[1] that we find pleasurable in social interactions. Anthropology and sociology literature seems to support this view, with the observation that analysis of common social interactions often reveals the coordinated production of sound and movement in what might metaphorically be described as a "dance." What we call dancing, usually to the accompaniment of music, in general consists of more structured, regularized, and exaggerated behavioral rhythms than those observed in social interactions, so it may be a fruitful area in which to develop and test systems that would allow social robots to perceive and exhibit rhythmic behaviors and participate in an interactive pro-

[1]Aristotle's *Poetics* proposes these as the two innate motivations for creating and enjoying art; we note that they are also fundamental to both dance and social interaction.

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cess of coordination and synchrony. We believe that investigating the effects of rhythmic synchrony in dance-oriented human-robot social interactions will be informative in designing robots that can perceive and behave according to natural rhythms in more open-ended interactions.

In this paper, we review literature that emphasizes the importance of rhythmic synchrony (the coupling of rhythmic patterns in verbal and nonverbal behavior) in social interaction, and we review robots that have made progress toward this end. We then present the system we have built, which can dance not only *to* music, but *with* a human dance partner in a coordinated way. The system consists of a robot, Keepon [17], and a software architecture that extracts rhythm from auditory and visual sensor data. To our knowledge, this system is novel both in the abstraction of rhythmic perception from a particular modality and in the agility and quality of its movement. Children were observed interacting with the system during a laboratory open house event for members of the community (fig. 1), with the aim of studying the ways in which children would physically and rhythmically interact with the robot. This was an exploratory study of a novel software architecture used to control a well-established, dynamic hardware platform in order to observe rhythmic interaction between people and the robot. While the task was centered around dancing, the interactions remained unconstrained so that we were able to observe a wide range of interaction styles that will inform future work. We expected that the rhythmic synchrony of the robot's movements with the music and the children would have an effect on the quality of interactions and the rhythmic behaviors of children. Our analysis and observations suggest that, indeed, this was the case; that music provided a powerful environmental cue for the negotiation of rhythmic behavior relative to that of the robot; and that the robot's responsiveness to people's behaviors positively affected their engagement with the robot. We additionally discovered possible gender differences in the degree of rhythmic movement and touching behavior with the robot.

2. RHYTHM IN SOCIAL INTERACTION

The past four decades have witnessed the emergence and development of a line of research spanning disciplines such as anthropology, psychology, and cognitive science in understanding the organizing principles for interaction between intelligent embodied agents. We now understand interaction not as a sequential process of give-and-take, but as a dynamic process of coordinated activity between constantly adapting participants. Together with behavior matching (or posture mirroring, the correspondence between positions or gestures assumed by two interactors [22, 18]), *interactional synchrony* provides a foundation for interpersonal coordination [3] and emotional contagion [13]. Interactional synchrony is the temporal coordination of communicative behaviors between interactors (often without awareness or volition) in order to achieve a sort of "goodness of fit" between them [4].

The rhythmic organization of social interaction is an expression of the oscillatory neurobiological language of the central nervous system through learned cultural patterns [5]. Two or more people coordinate their rhythms, achieving synchrony, through a process known as *entrainment* [7, 16], whereby multiple different rhythms converge on or capture each other. Given the important role of rhythmicity and synchrony in human interaction, it is clear that difficulties in establishing interactional synchrony can make face-to-face interpersonal communication and interaction difficult, if not impossible; in fact, marked asynchronies within an individual's own behaviors [8], along with abnormal entrainment in interpersonal interactions [6], are often characteristic of pathologies such as autism and schizophrenia.

Attention to the rhythmic characteristics of nonverbal interaction has not been widely adopted in social robotics research. General ideas of turn-taking in conversation are widely implemented, but fine-grained rhythmic perception and synchrony by a robot has been difficult to develop. Ogawa et al. [21] recognize the importance of rhythmic entrainment to non-verbal cues such as nodding and gesture in vocal communcation. In their InterRobot humanoids, which are used in pairs for embodied telecommunication between remote interactors, they use nonverbal rhythmic cues such as facial expressions and bodily movements that are automatically synchronized to the speech input of a remote human interactor. Andry et al. [1], with the view of interpersonal coordination as a method of learning, use synchronized imitation as a way for robots to learn sensory-motor correspondences and rhythmic motion sequences. The humanoid robot Nico [9] and the robot Haile [25] perform drumming synchronized to another person or a conductor as an example of the kind of rhythmic entrainment that might be applied to other social tasks.

In existing projects, rhythmic interaction is generally based on auditory cues and limited perception of embodied movement. However, robots should be able to "tune in" to the bodily rhythms of their interaction partners as well as to generate such nonverbal behaviors (e.g. nodding, swaying, gesturing) themselves. Tanaka et al. [23] created non-interactive and interactive (posture mirroring) dance modes for a QRIO robot in a playroom with children. They found a significant difference between the two conditions with respect to the time children spent with the robot, yet this experiment concerned contingency rather than the type of rhythmic synchrony we are developing. We have observed similar differences between contingent and non-contingent behaviors in rhythmic interaction between children and a robot-like puppet [19], and furthermore observed a higher incidence of rhythmic play by children when the robot behaved contingently.

Since both self-synchrony (rhythmic matching of movements and vocalizations) and interactional synchrony are important for normal human-human interaction [15, 8], these capabilities should be considered in designing robots that interact socially with humans. We now present a system that aims to achieve such synchrony in dance-centered social interactions, where rhythmic behavior is salient and regular, and therefore more readily perceived by the machine.

3. SYSTEM DESIGN

3.1 Hardware

The creature-like robot Keepon is designed to perform emotional and attentional communication with human interactors, especially children. Keepon has a snowman-like body (fig. 2). The upper part (the "head") has two eyes (each of which is a 120° wide-angle color CCD camera) and a nose (which is a microphone). The lower part (the "belly") has a small gimbal and four wires by which the body is ma-

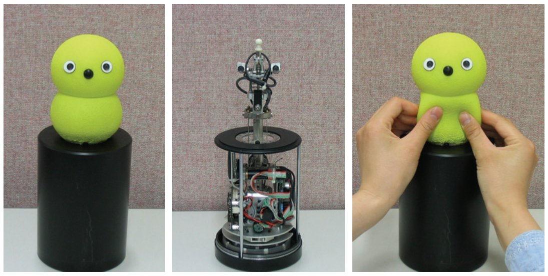

Figure 2: Keepon's external and internal structure and its deformable body.

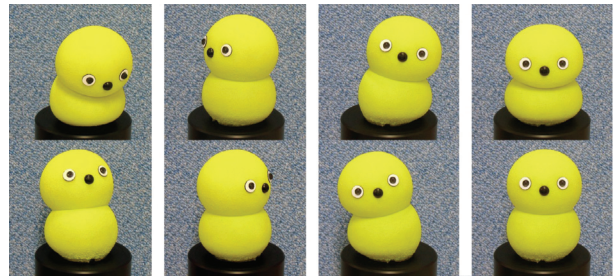

Figure 3: Keepon's four degrees of freedom (nodding, panning, rocking, and bobbing).

nipulated like a marionette. Keepon sits atop a black cylinder that contains four motors and two circuit boards (a PID controller and a motor driver). Since Keepon's body is made of silicone rubber and is relatively hollow, the head and belly deform whenever Keepon changes posture or when someone touches it.

The simple body has four degrees of freedom (DOFs), as shown in fig. 3: nodding/tilting $\pm 40°$, shaking/panning $\pm 180°$, rocking side-to-side $\pm 25°$, and bobbing/shrinking with a 15mm stroke. For each degree of freedom, the PID controller can be given parameters for maximum velocity and acceleration. Given a position command, the controller generates a trapezoidal velocity profile that smoothly accelerates and decelerates the motor to the desired position.

3.2 Software

A number of low-level software modules on the controlling computer are used for command generation and serial communication with the robot. High-level control (fig. 4) is implemented in Max/MSP [11], a graphical programming environment originally designed for controlling digital musical instruments. Max/MSP is well-suited to this application, as it provides tools and components for creating clocks and metronomes, performing audio signal processing, and designing graphical user interfaces. Communicating with hardware control modules (using sockets) and linking with external libraries (such as OpenCV [14]) is accomplished with external Max/MSP objects built in the C++ language.

An interface built in Max/MSP allows a human teleoperator to see the view from Keepon's eyes and to control the robot's pose or direction of attention. While it would be possible to run the robot autonomously using, for example, face recognition, having a human control the robot's high-level attentional state allows for more compelling social interactions while focusing on the relationship between the rhythmic behaviors of robot and interactor.

A metronome in Max/MSP produces a succession of beats separated by a given time interval to produce the desired beats per minute (BPM). The frequency of the master beat to which Keepon dances can be obtained either from auditory or visual sensing. The Max/MSP `sync~` object receives a series of taps (which may be keyboard or mouse presses, amplitude peaks in an audio signal, or any type of message) and returns the BPM of the last three approximately evenly-spaced taps. In the case of visual sensing, average optical flow in a region of interest is computed for an incoming video stream. Changes in direction (with hysteresis) are used as taps for computing the BPM of dominant movement in the environment (presumably that of a human dancing partner).

For each of Keepon's degrees of freedom, there is a cluster of Max/MSP objects that uses the beats of the master metronome, current BPM information, and the current position of Keepon's pose or direction of attention (controlled by an operator) in order to generate rhythmic movement centered on the current direction of attention. The parameters of each DOF are: a binary switch determining whether that DOF is active; a binary switch determining whether, for each beat, the DOF moves to one of its limits or through an entire cycle; a binary switch determining the phase; and the desired range of rhythmic motion for that DOF. These parameters are randomly selected and modified at random intervals in order to keep the dance interesting. Based on changes in the BPM or the magnitude of the DOF's range of motion, commands are first sent to the motor controller to set the DOF's maximum speed and velocity to ensure motion of appropriate speed (i.e., when the beat is slow, or the range of motion is small, Keepon moves slowly, and vice versa). With each metronome beat (or half-beat, if the DOF is to move through an entire cycle per beat) a command is sent to the motor controller to move the DOF to one of the limits of its desired range of motion.

4. OBSERVATION

4.1 Setup

Keepon was on display at the annual open house of Japan's National Institute of Information and Communications Technology. Members of the community, especially parents and children, were invited to see the various research projects undertaken at the Institute. Keepon was positioned atop a small table in a half-cubicle-partitioned area in a room with other robots on display. The floor on one side of the area, opposite Keepon, was tiled with carpeted panels to provide children with an affordance for dancing (see fig. 1). A sign hung on one of the partitions encouraged children, in Japanese, to "dance with Keepon!" Selections from a collection of well-known Japanese children's songs played randomly from speakers behind a partition.

Keepon was set up to extract rhythm from visual movement, rather than audio, with the goal that the robot would synchronize to the physical dancing of visiting children. Children would see a robot dancing to music, when in fact the robot was "deaf" to the music and could respond only to their movement. A small fixed camera was trained on the carpeted area for recording, and a subwindow of the video stream was used by Max/MSP to calculate movement from optical flow. The on-board cameras could not be used as it

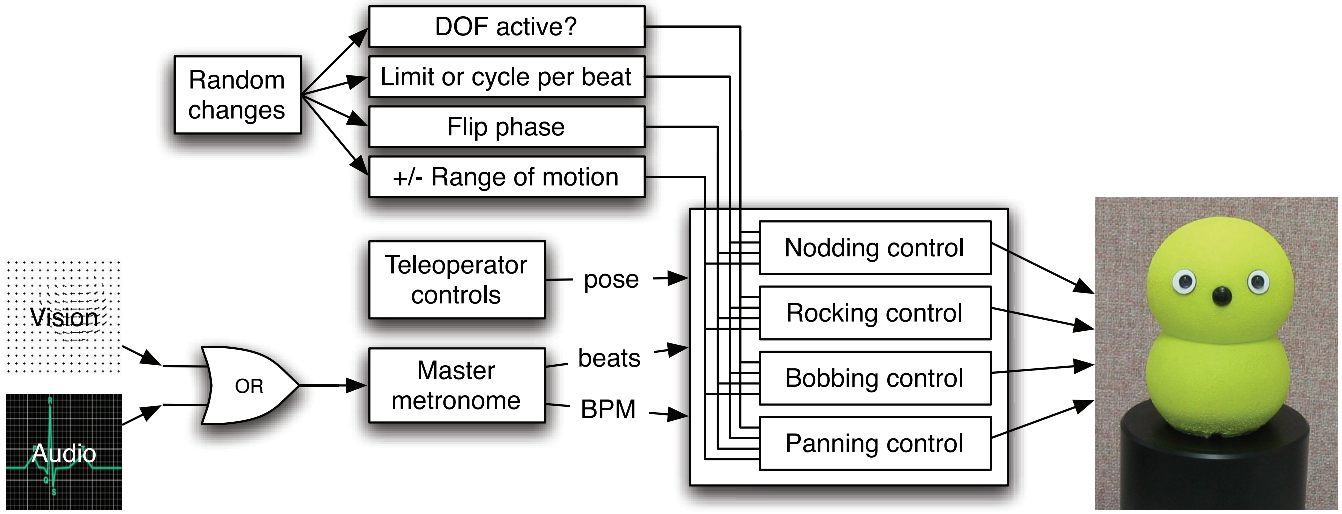

Figure 4: The dance control architecture for Keepon.

would be extremely difficult to isolate environmental movement from the robot's own movement. Keepon's general direction of attention was guided by an operator, but the rhythmic movement and dancing (centered around the direction of attention) was generated autonomously.

We recorded visitors interacting with the robot and analyzed the video to observe general patterns of behavior and, specifically, rhythmic behaviors. From five hours of recorded video, we isolated the segments (a total of one hour and forty-eight minutes) in which people interacted with the robot, where interaction is defined as visual attention, tactile contact, or bodily movement with the robot.

4.2 Initial analysis

Initially, we analyzed the video following a coding scheme designed to determine the effect of Keepon's synchrony to music on the rhythmic behavior of children who interacted with it. Half of the video (69 minutes), with the interactions of 116 children, was coded in this way. Since Keepon was responding to video rather than audio, the robot was at times synchronized to the music and at times not. For each child's interaction, a coder noted (a) whether Keepon was initially synchronized to the music as the child approached for interaction with the robot, and (b) whether the child then began to dance or perform clearly rhythmic behaviors synchronized with the robot or with the music.

About a third of the children (35 out of 116) who interacted with the robot performed some dance-like rhythmic behavior, from oscillatory hand movements to full-body physical exertion. The codes obtained from this analysis show that significantly more children started to dance with the robot when it was already dancing in synchrony with the music (having sensed movement in the environment that matched the tempo of the music) than when it was not ($\chi^2(1, N = 116) = 9.321, p = 0.0023$) (fig. 5). This suggested that the children were able to perceive properly synchronized movement, and that this recognition was a powerful motivator for turning passive interactions (such as observing and touching) into more active and engaged dancing interactions.

Although the quantitative significance of these results is suggestive, it should be noted that the codes were the result of rather subjective impressions on the part of the coder regarding Keepon's degree of synchrony as well as the nature of the resulting rhythmic behaviors by the child.

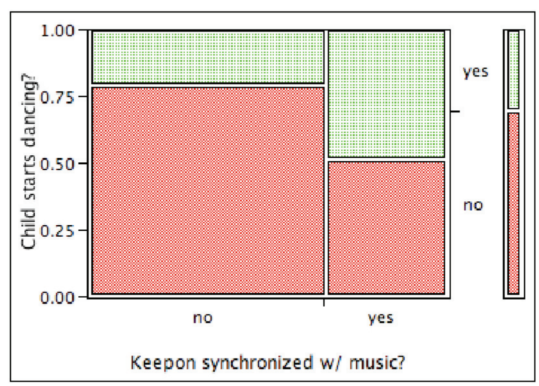

Figure 5: Whether children started dancing based on Keepon's initial synchrony with music.

4.3 Behavioral analysis of observational data

Encouraged by these results, we had a second coder analyze the video (in its entirety) using Noldus Observer software [20], which allows fine-grained, continuous labeling of the robot's and participants' behaviors for statistical and temporal analysis.

First, Keepon's synchrony with the music was coded for the duration of the video. For 38.6 minutes (37.9% of the time) Keepon danced in synchrony with the music, for 53.64 minutes (52.64% of the time) Keepon was out of synchrony with the music, and for the remainder of the time Keepon was not moving either due to silence between songs or because of minor technical interruptions in functioning. Keepon

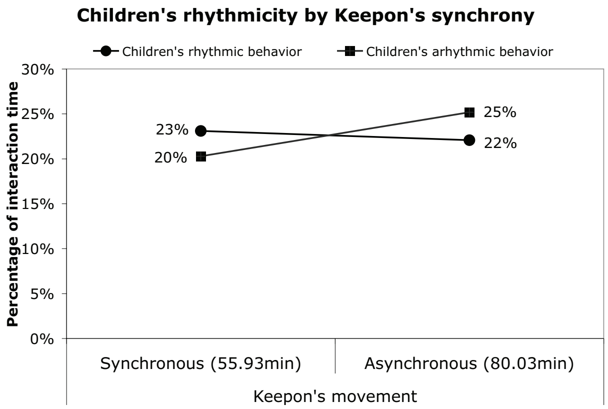

Figure 6: The percentage of interaction time children spent performing rhythmic or arhythmic behaviors according to Keepon's synchrony to music.

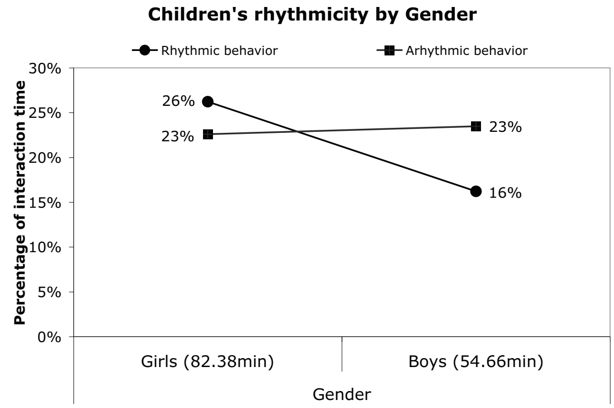

Figure 7: The percentage of interaction time children spent performing rhythmic or arhythmic behaviors according to gender.

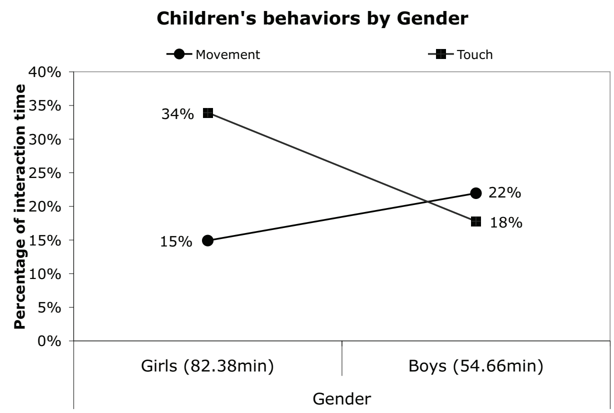

Figure 8: The percentage of interaction time children spent performing movements or touching behaviors according to gender.

was slightly more often not synchronized with the music either because people were not moving rhythmically to the music or because Keepon failed to perceive if they were. The beginnings of interaction sequences, in which children interacted with the robot individually, simultaneously in groups, or by taking turns, were evenly distributed over time: 38 interaction sequences began with Keepon synchronized to the music, 57 when not synchronized, and 17 when Keepon was not moving.

The behaviors of children who interacted with the robot, as well as their gender, were coded according to a scheme focusing on the rhythmicity of their movements and synchrony with the robot or the music. The scheme includes rhythmic dancing behavior such as bobbing, rocking back and forth, and full-body movements to the music; gesturing with the arms (synchronously or asynchronously with the music); touching the robot (tapping/patting just once, or repetitively; synchronously or asynchronously); and holding or stroking the robot.

We coded Keepon's interactions with 113 girls and 96 boys. Children of all ages interacted with the robot, from very young (approximately two years) to the mid-teens. It was impossible to accurately estimate age, but the estimated ages did not appear to have a significant effect on the behaviors we analyzed. The majority of interactions involved children interacting with Keepon in groups: only 25 children interacted with Keepon alone, 52 interaction sequences involved pairs of children, and 35 interactions involved 3 or more children.

Our main focus in coding, as before, was to see how the apparent synchrony of Keepon's behavior in its relation to the music affected the manner in which children interacted with the robot. For the children, there were two major rhythmic affordances in the environment: one was the almost constantly moving Keepon, and the other was the music. Although the rhythmic behaviors of other people in the environment can be expected to have an influence on children's behavior as well, we did not code people's interactions with each other as we were primarily interested in the development of interaction between the children and the robot.

We first examined the effect of Keepon's synchronous or asynchronous relationship with the music on the occurrence of corresponding rhythmic (bodily movement, gesturing, or touching the robot in a rhythmic manner in synchrony with the music) versus arhythmic (gesturing or touching the robot without apparent rhythm and not synchronous with the music) behavior by children. We determined the amount of time children spent performing rhythmic and arhythmic behaviors toward the robot as percentages of the total time that all children spent interacting with the robot in each of these two conditions (55.93 minutes when Keepon was synchronous, and 80.03 minutes when Keepon was asynchronous). In this method of coding, and in measuring percentages of time, we did not obtain the same statistical significance as in our initial analysis. However, figure 6 illustrates that we did find a trend in the same direction; that the synchrony of the robot's behavior to music resulted in more time performing rhythmic behaviors relative to arhythmic behaviors. Although quantitatively analyzing these kinds of interactions is unfortunately difficult due to high sensitivity to coding method, we believe that these preliminary results point to a phenomenon that requires and deserves further research.

Interestingly, the gender of the interacting children appears to have had an effect on the incidence of children's rhythmic behavior as well as on the relative amounts of movement and touching behaviors. While not statistically significant, figures 7 and 8 illustrate possible trends in these differences. We see that girls spent a higher percentage of their total interaction time (82.38 minutes) performing rhythmic rather than arhythmic behaviors, while for boys (total 54.66 minutes) this trend is reversed. Additionally, girls spent a higher percentage of their time touching Keepon, a phenomenon corroborated by our qualitative observations.

4.4 Qualitative observations

Many children did not dance at all, and we suspect that this is because the music was oriented for rather young children and because the demonstration took place in a large public space with mostly strangers. Additionally, a cultural embarrassment or modesty may have precluded free interpretation in a dance task that would normally involve more rigid structure or rules. As there was intentional ambiguity concerning what Keepon was responding to in the environment, we observed some confusion about what to do and the effects of one's behaviors on the robot's behavior. Given the difficulty of accurately sensing bodily movement using the simple method of optical flow, this confusion probably hindered the development of more involved interactions. In the cases where children were easily able to perceive the robot's responsiveness to their own rhythmic movement (perhaps a dozen cases), they exhibited a clearly recognizable enjoyment and satisfaction with the robot's performance.

Several of the children, and even some adults, began their interaction with Keepon by simply observing the robot for several seconds, and immediately began to nod or dance in rhythm with Keepon when Keepon's rhythm began to synchronize with that of the music. It appeared that there was a desire for the robot to behave in a rhythmically appropriate manner, and that when this desire was satisfied it provided a strong motivation to participate in the rhythmic activity.

Turkle [24] identifies different styles of relating to artifacts such as robots among seniors and children, expressed through both their explicit statements about the robots and their behaviors toward them. While we did not have an opportunity to ask children how they viewed Keepon, during our observations we noticed them displaying various behaviors toward the robot in interaction styles that might be roughly categorized as "exploratory" or "caregiving." For example, some children seemed to explore the robot as a mechanical object: we observed them closely examining the robot's internal and external cameras (interacting specifically with the external camera), testing the floor tiles to see whether stepping on them would elicit a reaction from Keepon, and squeezing the robot to feel what was inside the body. Some children positioned their heads near the robot as if to listen for sounds during movement. Other children enagaged in petting and stroking behavior as one would expect to see in interactions with an animal. These styles and behaviors are significant in terms of the children's ontological concepts of the robot and their models of its capabilities.

Even though the children were instructed only to "dance with Keepon," several children tried hard to make Keepon "do the right thing" and synchronize its movements to the music. Some children tried to provoke reactions from Keepon by waving, stomping around, or hitting the robot in time to the music. A number of children exaggeratedly danced to the music when Keepon was not synchronized, and even petted or grabbed the robot rather strongly in order to try to get it to move correctly, while other children went to great effort to imitate Keepon's movements very closely, sometimes to the point of ignoring the musical rhythm altogether. We also observed children mimicking the robot's morphological constraints; children seemed to mirror the robot's capabilities by bobbing their heads and torsos or rocking side to side. Synchrony to the music rather than to the robot (when the two were not synchronized) was more prevalent in children's behavior; this suggests that the auditory channel is possibly a stronger cue to rhythm than the movement of a small robot, and it would be interesting to determine whether the size of the robot has an effect on this trend.

Finally, we were distributing cell phone charms with an image of Keepon on them; several children made the charms "dance" in front of Keepon, often in rhythm with the music, as if Keepon had a special (perhaps communicative) relationship with the charms or would recognize a depiction of itself.

The range of interaction modes we observed with the robot makes direct statistical comparisons between children difficult, as they enter these open-ended interactions in an uncontrolled manner with very different sets of expectations, desires, and contexts for participation. However, as this was an exploratory study, the observations we made will be useful in the development of future interactions and studies with such a rhythmically capable robot.

5. DISCUSSION

The system we developed is general enough to be used to control other sufficiently agile robots. We are developing a morphologically similar robot to Keepon named Roillo [19], on which we intend to conduct controlled experiments concerning synchrony in dance and a child's comfort or interest in the interaction. Our exploratory study of Roillo with children showed that contingency and rhythmicity of interaction have an effect on perception of and interaction with a social robot or puppet. However, the difficulty of achieving autonomous rhythmic synchrony stems largely from a difficulty in perceiving what are often small changes in visual or auditory stimuli. Research in the rhythmicity of speech patterns is rather extensive, but motion to this point has been relatively unexplored. The optical flow method used here required that the interaction partner remain in a rather constrained space, which often failed in these freeform interactions.

To this end, we intend to continue investigating the problem of rhythmic motion perception from a number of different angles:

- We can look at how successfully we can detect oscillatory or repetitive movements in the environment from a camera using simple vision processes other than, or in addition to, the optical flow technique described here, such as face detection, skin color detection, feature tracking, etc. Crick [9] detected extremities in the spatial movement of the skin color of a "conductor's" hand, and we can imagine doing the same with head or body movements.

- In order to obtain more accurate information about human body movement during social interaction, we can look for repetitive or rhythmic movements in motion capture data. Ogawa [21] has developed a robotic telepresence system that allows two remote humans to communicate with each other through a pair of robots. The robots' physical behaviors are controlled by models of speech/motion correlation obtained from human speakers and listeners. They measure head, arm, and body motions using magnetic sensors, which provide similar data to motion capture data and are a promising alternative method.

- While the upper-body movements in children's freeform dance can be rather erratic, there appears to be a more regular vertical movement that might be exploited with the use of simple pressure sensors in the floor. In fact, a few participants mistakenly believed that the floor was in this way instrumented, similar to input devices for currently popular musical video games.

- We selected dancing as the task for our social interactions because the rhythmic properties of audio and movement are salient and regular enough to be easily sensed. Similarly, music production or performance, such as hitting a drum, is a task that would allow explicit rhythmic input and even the use of specific sensors for this purpose (e.g., an electrically instrumented drum). We have demonstrated Keepon dancing rhythmically to the beating of a modified drum fitted with a microphone. The movement of some other instrumented object or avatar, such as the cell phone charms observed here, is another possibility we intend to explore.

- As many children spent a large proportion of their time with the robot touching it, and some in fact tried to force the robot to move in a certain way, it is clear that proprioceptive recognition of rhythmic input might be the most powerful means of eliciting rhythmic play, satisfying the children's expectations of tactile contingency, and most importantly, feeding rhythmic information back to the children across a very salient sensory channel. Keepon's motors can be queried to provide a measure of the torque being applied. If this can be separated from the torque induced by Keepon's current movement, it would be possible to extract rhythm from any repetitions or regularities in externally applied force. Alternatively, or additionally, we can detect deformation in the body surface by embedding tactile sensors in the skin.

Perceiving rhythms in these different modalities is important not just for establishing rhythmic synchrony more effectively, but also for clearly and powerfully exhibiting responsiveness and contingency to the many different ways that people in unconstrained interactive situations might engage with the robot.

For further guidance on the design of interactive scenarios, we intend to observe dancers and instructors, e.g., how they synchronize, how an instructor corrects a student's errors, and how anatomical (corresponding body parts) or mirroring imitation is used. We can envision a task in which the robot tries to teach a child a particular dance and can evaluate whether the child is performing it correctly. We can consider interactive dance with a robot as an activity that can be used by clinicians to study a child's behavioral patterns and identify rhythmic abnormalities that could be useful in diagnosing certain pathologies. Dance has, in turn, been identified and used in therapies for a wide range of disorders [12, 10].

The dance-oriented human-robot interactions between Keepon and a child would at first appear to be dyadic. However, with music as a stable and unchanging[2] rhythmic presence, it might instead be considered a triadic interaction, with the music serving as a very salient and powerful time-giver. Alternatively, the music is seen as a part of the environmental context in which people operated. Children could (and did) synchronize with Keepon, with the music, with both, or with neither, and Keepon could only synchronize with the music indirectly by sensing movement in the environment. However, people hold a cultural model in which they expect that if Keepon can hear the music, it will dance appropriately. Differences in their expectations and behaviors, then, may be indicative of their model of Keepon's awareness of its environment.

The gender differences we observed were unexpected and warrant further investigation. Girls were generally more interactive than boys, particularly with respect to touching the robot and in their different responses to the robot's synchrony with music. This may be viewed in the context of the theory that girls tend to be empathetic while boys tend to be systematic [2], and can be explored with more direct conversation in order to identify ontological differences in gender-specific conceptions of the robot as machine, creature, or social partner.

Our initial method of coding, based on subjective impressions of the robot's synchrony to music and the rhythmicity of children's resulting behavior, suggested a more significant effect of the former on the latter than we were able to demonstrate with a more quantitative, time-interval-based method. While this demonstrates the importance of carefully designing both the interactive scenario and the analytical methods used to evaluate it, it should be noted that ours was an exploratory study that allowed us to observe a wide range of behaviors that will guide our future designs. In particular, we intend to perform experiments in controlling the robot's synchrony to entrain (in different ways) to particular perceived rhythmic behaviors by people. In this case, it will be necessary to perform a much more thorough analysis of resulting behaviors in video; specifically, by labeling individual interest points in movement or sound and determining frequencies of patterns in these modalities through fine-grained behavioral analysis. This data can then be temporally compared to logged rhythmic information received from sensors or sent to actuators in order to identify the effects of synchrony, not to music, but to the movements of interaction partners.

In terms of dynamic systems, the dance-oriented human-robot interactions described here are an example of co-regulation. Keepon and a child each respond to the other's movement; meanwhile, this response in turn serves to direct or guide the partner's movement. With the development of improved rhythmic perception and more salient responsiveness to these rhythms, we hope to produce a robot capable of participating in a process of interpersonal coordination through mutual adaptation and synchrony with interaction rhythms.

[2]This need not be so; the music might also be made to change tempo according to rhythmic movements of Keepon or the child.

6. CONCLUSION

We believe that the coordination or synchrony of subtle, nonverbal auditory and physical behaviors will be as much a prerequisite for comfortable, natural social interaction between humans and robots as we know that it is between humans and humans. We have presented a robot that is able to perceive, in multiple modalities, rhythmic properties of the environment and to generate synchronized rhythmic movement. We demonstrated the system in unconstrained interactions with hundreds of children in which dancing was the target activity. Our analysis of these interactions suggests that synchrony in the robot's behavior had an effect on people's rhythmic behavior, and we have discussed a number of directions for future work. We believe that using dance as a nonverbal social interaction between robots and children is an ideal environment in which to develop and evaluate technologies that allow robots to naturally participate in rhythmically synchronized social interactions.

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